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# Application of an offshore wind farm layout optimization methodology at Middelgrunden wind farm

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## Abstract

This article explores the application of a wind farm layout evaluation function and layout optimization framework to Middelgrunden wind farm in Denmark. This framework has been built considering the interests of wind farm developers in order to aid in the planning of future offshore wind farms using the UK Round 3 wind farms as a point of reference to calibrate the model. The present work applies the developed evaluation tool to estimate the cost, energy production, and the levelized cost of energy for the existing as-built layout at Middelgrunden wind farm; comparing these against the cost and energy production reported by the wind farm operator. From here, new layouts have then been designed using either a genetic algorithm or a particle swarm optimizer. This study has found that both optimization algorithms are capable of identifying layouts with reduced levelized cost of energy compared to the existing layout while still considering the specific conditions and constraints at this site and those typical of future projects. Reductions in levelized cost of energy such as this can result in significant savings over the lifetime of the project thereby highlighting the need for including new advanced methods to wind farm layout design.

**Keywords:** offshore wind farm layout optimization, levelized cost of energy, genetic algorithm, particle swarm, Middelgrunden wind farm

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## 1. Introduction

As offshore wind farms continue to grow it has become increasingly important to ensure that these projects are managed as efficiently as possible. With this in mind, the field of offshore wind farm layout optimization has grown to include sophisticated methodologies for the evaluation of the levelized cost of energy (LCOE) of offshore wind farms which includes both the lifetime energy production and lifetime costs of the wind farm. The LCOE, is frequently used by project developers to evaluate the impact a change in design might have on a project. This metric is also preferred as it is technology agnostic and therefore gives a basis by which projects of different technology types can easily be compared against one another.

The present work expands on the standard paradigm for the optimization of offshore wind farm layouts in which wake and cost models are integrated as the evaluation function for an optimization algorithm. This work shows that a sophisticated and detailed LCOE evaluation tool can successfully be included in the optimization process accounting for realistic constraints faced by a wind farm developer. Taking the UK Round 3 wind farms as a point of reference, the present tool built in partnership with wind farm developers, has been developed to aid in the planning of these wind farms allowing the developer to explore wind farm layout alternatives. Given the future application to UK Round 3 sites, much of the tool has been calibrated to these sites and sites of similar site characteristics. Extending the previous work of the authors [1], the present work allows the wind farm to be designed considering different degrees of layout restriction which may potentially be imposed by regulatory bodies.

This article explores Middelgrunden wind farm, a wind farm off the Danish coast, as a test case to both verify the full LCOE evaluation function and highlight potential improvements that could have been achieved through more optimal turbine placement using either a genetic algorithm (GA) or a particle swarm optimizer (PSO). By applying the layout optimization framework to a real wind farm site rather than to fictional cases the capabilities and applicability of the present wind farm layout optimization tool are demonstrated.

The field of wind farm layout optimization was initially explored in the seminal work by Mosetti et al. [2] in which three fictional wind farm sites were defined and wind farms optimized using a genetic algorithm. Following the inception of the field of optimization of wind farm layouts, the cases de-

38 fined by Mosetti et al. [2] have been revisited and used as a benchmark. The  
 39 field has explored a number of different optimization algorithms to this prob-  
 40 lem including genetic algorithms [3–12], particle swarm optimizer [13], viral  
 41 based optimization [14], pattern search [15], mixed-integer linear program-  
 42 ming [16], and Monte Carlo simulation [17]. The most frequently deployed  
 43 optimization approach has been the genetic algorithm and though much work  
 44 has focused on the development and evolution of the optimization algorithm,  
 45 little of the existing literature has explored the evolution of the evaluation  
 46 function beyond testing alternate wake models. Detailed reviews in the field  
 47 of wind farm layout optimization have been compiled by Tesauro et al. [18]  
 48 and Herbert-Acero et al. [19].

49 As the original work by Mosetti et al. [2] explored the applicability of  
 50 the genetic algorithm to this problem, it ignored the layout dependent costs.  
 51 Many of the developed tools following this have also focused on the appli-  
 52 cability and development of the optimization and have therefore opted to  
 53 use cost functions that either omit important layout dependent factors or  
 54 which ignore the layout all together thereby only considering the impact  
 55 the layout has on the energy produced. The work by Elkinton [4] repre-  
 56 sents an exception in which a detailed cost model was built and verified.  
 57 This, however, was developed based on published data at the time and has  
 58 limited applicability to new projects. As the aim of the existing tools has  
 59 been to further develop the optimizers rather than industrial applications  
 60 of the methods, it remains challenging for the developed wind farm layout  
 61 optimization tools and methodologies to be deployed in the design of real off-  
 62 shore wind farms. Focusing more on the potential industrial applications, the  
 63 present work therefore both represents a more detailed evaluation function  
 64 over previous work and also applies the full methodology to a more complex  
 65 wind farm site with realistic constraints faced by developers. Furthermore,  
 66 the development of the present framework has allowed two of the leading  
 67 metaheuristic optimization algorithms applied to offshore wind farms to be  
 68 deployed on the same framework allowing a direct comparison.

69 Through the deployment of this tool for an existing wind farm it is pos-  
 70 sible to gauge the tool’s suitability to future wind farms and identify areas  
 71 in which the tool will need to be further developed in order for the results to  
 72 be of use to a site developer.

## 2. Methodology

The developed approach makes use of a modular framework for the assessment of offshore wind farm layouts. As is shown in fig. 1, the evaluation of a layout is divided into three separate steps. The LCOE by definition requires the computation of the AEP and the lifetime costs as shown in eq. (1), however, a wind farm’s electrical infrastructure (substation position, intrarray cable paths, and intra-array cable specifications) impacts both of these terms; changes in the electrical infrastructure affect the energy losses and therefore the AEP while at the same time changes in the electrical cabling and substation position can directly affect the costs. The first step in the evaluation of the LCOE is therefore for the necessary electrical infrastructure to be determined for a given turbine layout. Following this, the annual energy production (AEP) for the wind farm is computed considering not only the wake losses, but also the losses due to the electrical infrastructure; and finally, the relative costs of the project over its lifetime are estimated. From these three components, the LCOE of the layout is computed and as a result, the optimizers can use this information to make informed decisions on how the solutions should evolve between generations.

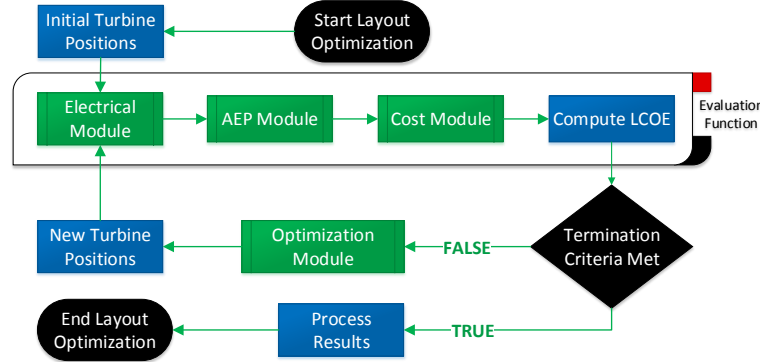


Figure 1: Modular approach to wind farm layout optimization.

The LCOE is defined to be a function of both the total energy generated and the costs over the lifetime of the wind farm:

$$LCOE = \frac{\sum_{t=1}^n \frac{C_t}{(1+r)^t}}{\sum_{t=1}^n \frac{AEP_t}{(1+r)^t}} \quad (1)$$

where  $C_t$  is the total costs incurred in year  $t$ ,  $n$  is the project lifetime,  $AEP_t$ , is the annual energy production in year  $t$ , and  $r$  is the discount rate of the project.

As European regulators are currently in discussions with wind farm developers to develop guidance on how layouts are to be designed in the future, there are different levels of constraint which are of interest to developers depending on the final decisions made by the regulators and licensing bodies [20]. In order to accommodate these different levels of constraint, the present framework has three separate modes of operation which address these different constraints:

1. **Array Mode** - The decision variables define the spacing and orientation of a regular grid of turbine positions with constant downwind and crosswind spacing throughout the site. This produces layouts with clearly defined navigational channels and is preferred by some regulators due to stakeholders concerns such as those raised by the Maritime Coastguard Agency in the UK [20].
2. **Binary Mode** - The wind farm area is discretized into allowable turbine positions and the decision variables are therefore binary variables representing the presence of a turbine in a particular cell. Wind farm developers are interested in this approach as it allows them to have much of the regularity that regulators seek with the array mode, but could allow for more innovative layouts that better use the site in question. In this scenario, the discretized allowable turbine positions could be imposed directly with the regulator or be developed through discussions between the wind farm developer, regulator, and other stakeholders.
3. **Continuous Mode** - The decision variables directly define the turbine coordinates and may therefore occupy any value within the wind farm area. Using these constraints, there are no externally regulator/stakeholder imposed constraints on the positions of the turbines

and this therefore represents the case in which the wind farm developer is free to develop the site as they see best.

### 2.1. Electrical Infrastructure Optimization

As part of the development of this layout optimization framework, a sub-tool has been developed to address the optimization of an offshore wind farm’s electrical infrastructure. This is fully presented by Pillai et al. [21]. This sub-tool implements a heuristic approach and is therefore not guaranteed to find the proven optimal solution, however, it takes a pragmatic approach, identifying good feasible solutions in an acceptable run time. As part of this sub-tool, given the turbine positions, number of offshore substations, voltage level of the connection network, and the cable parameters, the offshore substation positions are determined as well as all intra-array cable paths, and cable sizes. In the case of Middelgrunden wind farm, there is no offshore substation and therefore this sub-tool is only used to determine the cable paths considering the voltage level and the cable specifications/limits.

Within this sub-tool, a pathfinding algorithm is executed to determine the possible cable paths which could connect the wind farm. For the present case study, the pathfinding algorithm was run between all turbine pairs allowing any turbine to potentially be connected to any of the other turbines or the onshore connection point. The pathfinding algorithm is used to ensure the consideration of seabed obstacles which define where the cables cannot be placed. Using the accurate lengths of cables determined by the pathfinding algorithm, a capacitated minimum spanning tree (CMST) problem is formulated and solved using the commercial MILP solver Gurobi [22]. The solution to the CMST identifies which of the possible cables should be deployed in the final network. In this way, the pathfinding step defines all the possible cables to consider and their accurate lengths, while the CMST selects which of these cables should be used to minimize the cost of the infrastructure.

In Pillai et al. [21] this methodology is presented in full and demonstrate that this new methodology can be necessary for large offshore wind farms which may need to consider a number of obstacle regions where either cables or substations cannot be placed. Though cable path optimization has previously been previously explored using a MILP formulation by Fagerfjäll [16]; Lindahl et al. [23]; Bauer and Lysgaard [24]; and Dutta and Overbye [25], the present methodology has greater capabilities in the handling of complex seabed constraints which are now faced by wind farm developers at future sites. Inclusion of such a detailed cable path optimization within the offshore

wind farm layout optimization problem has previously not been undertaken, however, is a feature sought by wind farm developers.

## 2.2. Annual Energy Production

Due to the extraction of energy, wind turbines impact the air flow reducing the wind speed and increasing the turbulence directly behind an operating wind turbine [26–29]. As a result of this, the wind farm layout has a major impact on the wind speeds that each individual wind turbine within the wind farm experiences and therefore a direct impact on the energy produced by the wind farm. It is therefore important that the wind turbine wakes are accounted for.

The calculation of the AEP is done in a traditional approach which accounts for the wake losses throughout the wind farm using the analytic wake model developed by Larsen [30]. This wake model has been deployed here as validation at several existing wind farms has demonstrated that it represents a good compromise between computational speed and model accuracy when used to compute the AEP of an offshore wind farm [31, 32]. Though there are models which have been able to more accurately estimate the AEP such as those based on computational fluid dynamics, these require additional computational time rendering them less effective when deployed in the optimization process where the AEP calculation will be done for each layout considered.

To compute the AEP, each wind speed and direction combination are stepped through in sequence using  $1 \text{ m s}^{-1}$  and  $30^\circ$  bins. For each free wind speed and wind direction the analytic wake model is used to update each turbine’s incident wind speed based on the performance of all upwind turbines. From this, the wind turbine power curve is used to convert the wake affected incident wind speed to the energy produced under these conditions [33, 34]. For each wind speed and direction combination, the electrical cable losses are then computed based on each turbine’s individual contribution to the AEP using an IEC based methodology [35–37]. Following this, the total wind farm contribution to AEP under the given free-stream wind speed and direction is updated. This total production for each wind speed and direction combination is then scaled by the probability of occurrence of this combination for the site in question before being added to the AEP.

$$AEP = 8766 \times \sum_{\theta_i} \sum_{v_i} P(\theta_i, v_i) \times [E(\theta_i, v_i) - L(E(\theta_i, v_i))] \quad (2)$$



194 where  $\theta_i$  is the wind direction;  $v_i$  is the wind speed;  $P(\theta_i, v_i)$  is the joint  
195 probability of  $\theta_i$  and  $v_i$ ;  $E(\theta_i, v_i)$  is the energy production for the wind farm  
196 for the combination of free wind speed and direction considering the wake  
197 losses; and  $L(E(\theta_i, v_i))$  is the electrical losses associated with the energy  
198 production as a result of the intra-array cable network.  $E(\theta_i, v_i)$  therefore  
199 represents the gross energy measured at each turbine nacelle, while  $E(\theta_i, v_i) -$   
200  $L(E(\theta_i, v_i))$  represents the net energy delivered to the grid.

### 201 2.2.1. *Larsen Wake Model*

202 In the computation of the AEP, this tool makes use of the Larsen wake  
203 model [30]. This wake model is an analytic wake model which models the  
204 reduction in wind speed as a result of an operating wind turbine. The model  
205 is based on a closed-form solution to the Reynolds-Averaged Navier-Stokes  
206 (RANS) equations based on Prandtl mixing theory [30, 38]. The full for-  
207 mulation of this model is given in Larsen [30]; Larsen [38]; and Tong et al.  
208 [39].

209 This model uses the wind farm layout, wind speed, wind direction, ambi-  
210 ent turbulence intensity, and the turbine thrust curve to estimate the wind  
211 speed deficit at a desired downwind location. By iterating through the tur-  
212 bines starting with the most upwind turbine given the wind direction, the  
213 wind speed deficit can then be computed for each turbine in sequence thereby  
214 determining the effective wind speed observed by each turbine for the given  
215 conditions. The effect of multiple and overlapping wakes is taken into account  
216 using a root-sum-square method [31, 32].

### 217 2.3. *Cost Estimation*

218 Previous tools that have included a cost model have typically not been  
219 able to validate their cost models, and as a result have introduced significant  
220 uncertainty into the optimality of their solutions [4, 16]. As this tool has  
221 been developed in conjunction with an offshore wind farm developer, it has  
222 been possible to directly develop, calibrate, and validate the cost assessment  
223 methodologies against real industry costs. Consequently this work presents  
224 costs that have been parameterized and validated against the real costs to  
225 be incurred by large offshore wind farms deploying wind turbines in the 5-8  
226 MW range in UK waters. Some discrepancy is therefore anticipated as in  
227 this study, the model is being applied to a much smaller offshore wind farm,  
228 utilizing smaller wind turbines, and located in Danish waters.

From discussions with wind farm developers and component suppliers, the total cost of the wind farm is divided into eight major cost elements each with varying degrees of sensitivity to the layout qualitatively described in table 1 based on how the layout is considered in the calculation of each individual cost element. Each cost element is attributed to being part of the capital expenditure (CAPEX) incurred during the construction period of the wind farm, the operational expenditure (OPEX) incurred annually during the operational period of the wind farm, or the decommissioning expenditure (DECEX) incurred during the decommissioning period at the end of project life. For each of the cost elements, industry standard assumptions for vessel parameters have been assumed.

Table 1: Cost Element Contribution to CAPEX, DECEX, and OPEX

Cost Element	CAPEX	DECEX	OPEX	Sensitivity to Layout
Turbine Supply	✓	-	-	Low
Turbine Installation	✓	-	-	Medium
Foundation Supply	✓	-	-	Medium
Foundation Installation	✓	-	-	Medium
Intra-Array Cables	✓	-	-	High
Decommissioning	-	✓	-	Medium
Operations and Maintenance	-	-	✓	Medium
Offshore Transmission Assets	✓	-	✓	Low

### 2.3.1. Turbine supply

The turbine supply costs are determined based on the price per turbine including tower that turbine manufacturers have provided through discussions with various members of the offshore wind industry. This cost therefore does not vary due to the layout unless the total number of turbines or installed capacity changes.

### 2.3.2. Turbine installation

Each of the installation stages takes a time based approach in which the time required for the installation operations is computed and then computed to a cost based on the vessel and crew day rates [40, 41]. The turbine installation costs are based on market values for vessel costs and capacities. These costs are modeled by first calculating the expected time required to install all the turbines at their specific locations. This includes not only the

253 computation of the travel time between the turbines, but also the necessary  
 254 time to go to and from the construction port. To calculate this, the turbines  
 255 are clustered based on the capacity of the installation vessel, and for each  
 256 cluster a shortest path is computed between the port, each turbine in the  
 257 cluster, and the port again using Dijkstra’s algorithm. This approach there-  
 258 fore accurately computes the distance that the vessel must traverse during  
 259 the installation process. From this, the total time is computed based on  
 260 assumed weather availability and time required for each operation once at  
 261 the turbine positions. The costs are then computed based on the vessel and  
 262 equipment day rates. The turbine layout, therefore, has a direct impact on  
 263 the time needed to travel between turbine positions as well as to and from  
 264 the port. This cost model differs from common approaches through the use  
 265 of the clustering and pathfinding algorithms used to determine the distance  
 266 that the vessel must cover in the installation procedure. This is a necessary  
 267 element to characterize the impact that the wind farm layout has on the  
 268 costs.

### 269 *2.3.3. Foundation supply*

270 The foundation supply costs include the cost of the transition piece and  
 271 delivery of a fabricated foundation to the installation port. Foundation costs  
 272 are found to be highly dependent on the site conditions where the foundation  
 273 is to be installed. To account for this dependence, previous cost models have  
 274 attempted a bottom up approach based on the soil characteristics at the in-  
 275 stallation site to model the costs. Unfortunately this approach has proven  
 276 difficult to validate for all types of foundations due to the very detailed in-  
 277 put data required [4]. Furthermore, wind farm layout optimization tools are  
 278 generally deployed in early stages of the wind farm design at which point  
 279 detailed soil surveys have not always been completed. In order to remain ap-  
 280 plicable to the use case of wind farm developers it was found that simpler cost  
 281 models would be needed. The present tool therefore makes use of separate  
 282 empirical relationships for gravity based foundations, monopiles, and jackets  
 283 which have been developed from discussions with manufacturers. Specific  
 284 soil conditions are not included, however, the water depth, turbine size, and  
 285 turbine loads are. Detailed bathymetry of the site is therefore necessary in  
 286 order to estimate the variation in gravity based foundation supply costs as  
 287 a function of the turbine layout [42, 43]. As Middelgrunden wind farm has  
 288 turbines installed on gravity based foundations, only this cost relationship is  
 289 used in the present study.

290 *2.3.4. Foundation installation*

291 The foundation installation process, like the turbine installation module,  
292 is based on estimating the time required to complete the operations and  
293 converting this time to a cost. Unlike the turbine installation though, this is  
294 modeled as three distinct phases which each use a different vessel to complete.

295 Regardless of the foundation type (gravity-based, monopile, or jacket),  
296 some seabed preparation is necessary. For a gravity-based foundation this  
297 might be the necessary dredging and leveling of the seabed, while for monopiles  
298 and jackets this would more likely be pre-piling works including surveying  
299 and drilling. After this step, the foundations will be installed as a sepa-  
300 rate operation following which some kind of scour protection will often be  
301 added. The installation of scour protection is again modeled as a separate  
302 step involving a different vessel from either the site preparation or foundation  
303 installation processes. The cost of the material used for scour protection is  
304 included in this step rather than the foundation supply costs. In some condi-  
305 tions, the scour protection will not be necessary, however, for the time being  
306 this model has assumed that all turbines will require scour protection.

307 *2.3.5. Intra-array cable costs*

308 The intra-array cables are decomposed into horizontal lengths which are  
309 buried and connect between turbines, and the vertical lengths which connect  
310 from the seabed to a turbine nacelle. The vertical lengths therefore include  
311 consideration of the water depth at the turbine position and the turbine  
312 hub height. The total horizontal length of the required intra-array cables  
313 is computed from the intra-array cable optimization tool described in sec-  
314 tion 2.1. This tool has the capability for optimizing the layout for different  
315 cable cross-section sizes and therefore can output not only the total length of  
316 cable, but the horizontal lengths required for each segment and the required  
317 cross-section. From this, the intra-array cable cost module computes the  
318 necessary vertical cable and the necessary spare cable before computing the  
319 costs.

320 The installation cost for the intra-array cables is computed in a similar  
321 manner as the turbine and foundation installation modules. This is done  
322 based on data available for cable trenching vessels and therefore assumes  
323 that all cables are trenched and buried.

### 324 2.3.6. Offshore Transmission Assets

325 Regulators in different countries each have different ways in which the  
326 offshore transmission assets are handled and which of these costs are incurred  
327 by the wind farm developer. In Denmark, the offshore substation (if present),  
328 the offshore export cable, and onshore works are all built and owned by the  
329 Transmission System Operator (TSO) Energinet.dk. As a result, there is no  
330 need when considering Danish projects to include these cost elements as they  
331 are not incurred by the project developer.

### 332 2.3.7. Operations and Maintenance

333 The operations and maintenance (O&M) costs are modeled based on the  
334 anticipated operations and maintenance costs for projects in the 500 MW  
335 to 1000 MW. These costs are then modeled as a function of both with the  
336 capacity of the wind farm and its distance to shore. As this term is impacted  
337 by distance of the wind farm to the operations and maintenance port, this  
338 too is affected by the layout. The operations and maintenance costs are  
339 classed as operational expenditure (OPEX) as these are incurred annually in  
340 each year of operation.

### 341 2.3.8. Decommissioning

342 The decommissioning costs include the removal of the turbines and foun-  
343 dations. Presently, it is unclear what will happen to the transmission and  
344 export cables at the end of life, and the model therefore assumes that these  
345 cables are not removed at the time of decommissioning, but simply cut at the  
346 turbines and substation, leaving the buried lengths as they are. The decom-  
347 missioning costs are therefore modeled similar to the turbine and foundation  
348 installation processes. The time requirements for each vessel is first computed  
349 and this is then converted to a cost based on the vessel day rates [40, 41].  
350 Like the installation processes it is assumed that the vessels have some ca-  
351 pacity and must return to the decommissioning port prior to completion  
352 of the overall operation. The turbines and foundations are assumed to be  
353 decommissioned in separate steps requiring separate vessels. Like the instal-  
354 lation phases, this term is therefore dependent on the turbine positions and  
355 is affected by the layout under consideration.

## 356 2.4. Optimization Algorithms

357 The final step of the framework is to integrate an optimization algorithm  
358 to the evaluation in order to propose new layouts which are evaluated us-

ing the LCOE function described above. For the present work, a genetic algorithm (GA) and a particle swarm optimization (PSO), two algorithms commonly used in engineering applications, have been implemented and applied to Middelgrunden. For both algorithms, the problem was addressed exploring three different levels of constraint corresponding to different constraints that regulators are considering for wind farms [20].

Given the complexity of the wind farm layout optimization evaluation function and thereby the decision problem, population based metaheuristics were thought to be well suited as these have been shown to be effective ways of exploring complex search spaces. Metaheuristics by definition identify good solutions in an acceptable time frame and do not guarantee that an optimal solution is found. For complex search spaces, however, they represent a pragmatic approach for identifying a relevant feasible solution. Though other algorithms such as gradient decent, interior-point methods, and classical techniques could be deployed for this problem, it is believed that population based algorithms would be more capable. Within the family of population based algorithms, the GA and PSO are thought of as fundamentally different types of algorithms as GAs take on a competitive approach within the population while PSOs take on a cooperative approach. Though the GA has been deployed to a range of engineering problems, usually to quite successful results, the PSO is a younger algorithm that has not seen as frequent deployment. Given that the present framework has been developed in part to allow different algorithms to be compared within the same framework, using the same problem formulation and evaluation function it was decided that these two algorithms would be explored.

#### 2.4.1. Genetic Algorithm

The genetic algorithm represents a metaheuristic algorithm commonly deployed to aid in decision making and engineering design. In existing work, the GA has been frequently applied to wind farm layout design [19].

The GA is so named because it borrows principles from biology and evolutionary processes to generate and test new solutions. Each generation of the GA begins with *selection* through which pairs of individuals already in the population are chosen, based on the quality of their solutions, to contribute genetic material to the next generation. These pairs of individuals are combined through the *crossover* and *mutation* operators to generate new solutions referred to as child solutions. These child solutions take part of their parents' solutions through crossover, and are then potentially randomly al-

396 tered during mutation. Through these two operations the GA attempts to  
 397 retain the good elements of the parents in the newly generated children, and  
 398 the random element is included to aid in the avoidance of local solutions.  
 399 A *replace weakest first* replacement strategy is then employed to determine  
 400 which of the new generated children are included in the next generation.  
 401 This process of selection, crossover, and mutation repeats until an identified  
 402 proportion of the population has been replaced and the overall population  
 403 has improved in quality which marks the end of a generation. In general  
 404 GAs continue for a predefined number of generations or until there is insuf-  
 405 ficient diversity within the population, that is until the number of unique  
 406 members of the population falls bellow a threshold value. The overall flow of  
 407 the GA is shown in fig. 2. Though both crossover and mutation consider the  
 408 constraints, after both crossover and mutation, the constraints are explicitly  
 409 imposed, and if a child solution fails to satisfy any of the constraints then  
 410 crossover and mutation are repeated until it does [44, 45].

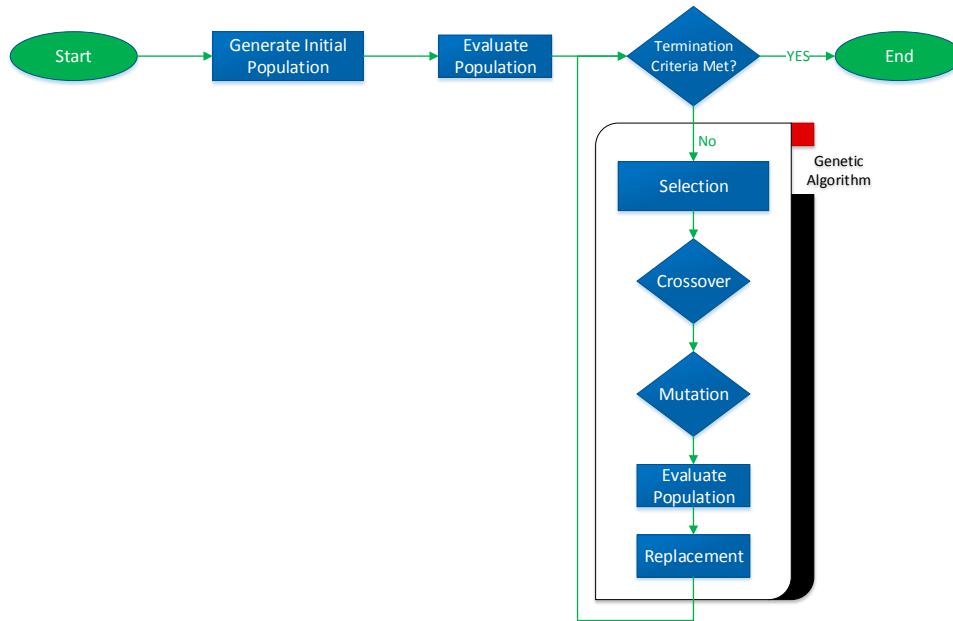


Figure 2: Genetic algorithm overview

411 In order to improve the convergence rates and the avoidance of local so-

lution, the probabilities associated with crossover and mutation have been made adaptive in the implemented GA and are functions of the quality of the solution. In this way, a better solution not only has a higher probability of being selected, but also a higher probability of contributing through crossover. The crossover and mutation probabilities are therefore a function of the solution's fitness value ( $f$ ) or the fitness value of the best parent ( $f'$ ) compared to the population's mean fitness ( $\bar{f}$ ) or the population's best fitness ( $f_{max}$ ).

The below formulations ensure that as the population converges, as measured by the difference between the fitness of the best individual and the mean fitness value of the individuals in the population, both higher crossover and mutation rates are applied to increase the exploration parameters of the GA and avoid premature convergence. At the same time, to preserve the better solutions in the population, crossover and mutation rates are decreased for these individuals.

$$p_c = \frac{k_1 (f_{max} - f')}{f_{max} - \bar{f}} \quad \text{for} \quad f' \geq \bar{f} \quad (3)$$

$$p_c = k_3 \quad \text{for} \quad f' < \bar{f} \quad (4)$$

$$p_m = \frac{k_2 (f_{max} - f)}{f_{max} - \bar{f}} \quad \text{for} \quad f \geq \bar{f} \quad (5)$$

$$p_m = k_4 \quad \text{for} \quad f < \bar{f} \quad (6)$$

where  $p_c$  and  $p_m$  are respectively the probability of crossover and mutation. The constants are defined such that  $k_1 = k_3 = 1$  and  $k_2 = k_4 = \frac{1}{2}$ . The use of adaptive parameters like this has been found to both aid in the rate at which the process converges as well as its ability to avoid local solutions [46, 47].

#### 2.4.2. Particle Swarm Optimizer

An alternate population based optimization algorithm is the particle swarm optimizer (PSO). This algorithm considers the candidate solutions as particles exploring the search space. From generation to generation, the particle's position within the search space changes depending on the quality of its current position relative to the best position the particle has historically occupied and the best historical position within the swarm at large. This process is shown in fig. 3.



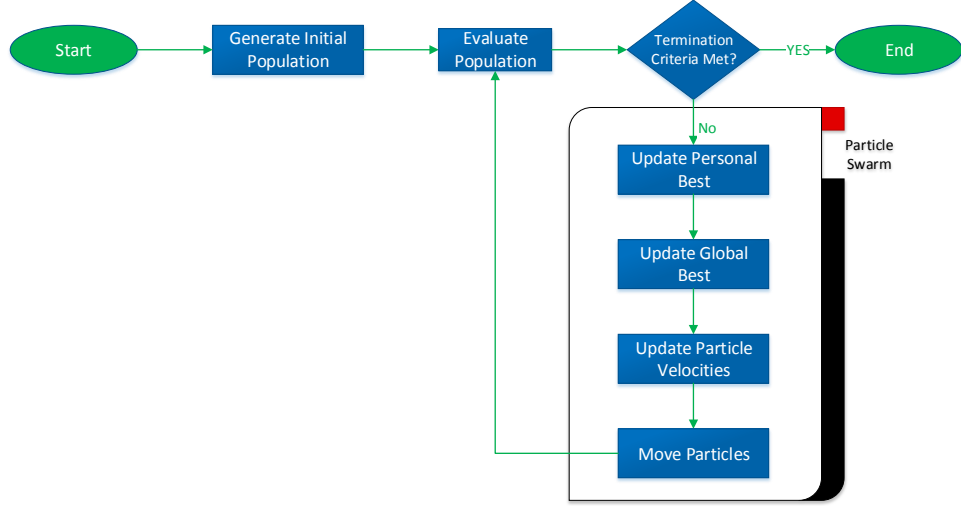


Figure 3: Particle swarm optimization overview

440 The particles' change in position within the search space is given each  
 441 iteration by the velocity. A particle's velocity in iteration  $i$ ,  $v_i$  is given by:

$$v_i = w_i v_{i-1} + C_1(p - x_{i-1}) + C_2(g - x_{i-1}) + C_3(\eta - x_{i-1}) + C_4 \times rand \quad (7)$$

442 where,  $w$  is an inertia weight determined by tuning the PSO;  $C_1$ ,  $C_2$ ,  $C_3$ ,  
 443 and  $C_4$  are coefficients representing the weighting of each of the contributors  
 444 determined by tuning the PSO;  $p$  is the best position that the particle has  
 445 historically occupied within the search space;  $g$  is the best historical position  
 446 that the swarm as a whole has ever occupied;  $x$  is the solution under con-  
 447 sideration;  $\eta$  is the best historical position that the neighborhood as a whole  
 448 has ever occupied; and  $rand$  is random number between 0 and 1. With this  
 449 velocity the particle's position the next iteration is given by:

$$x_i = x_{i-1} + v_{i-1} \quad (8)$$

### 450 3. Case Description

451 Middelgrunden wind farm, an offshore wind farm 5 km from Copenhagen,  
 452 is one of the earliest offshore wind farms and presents an interesting case for

the application of this methodology as site and production data are publicly available. Though this is a relatively small wind farm, made up of only twenty Bonus 2 MW turbines, it still provides an interesting test case as the evaluation function can be verified for this site and the full optimization framework can also be applied.

The data available publicly includes a high level CAPEX breakdown as well as the SCADA data from 2001-2004 which contains the wind speed, wind direction, ambient turbulence intensity, and production of the wind farm at 10 min intervals. Complementing this, data from the British Oceanographic Data Centre (BODC) and the General Bathymetric Chart of the Oceans (GEBCO) to provide bathymetric data at a 30'' resolution [48]. This combination of data provides sufficient information for the evaluation function and therefore for the full optimization methodology to be applied for this real site. The site data used for this study are described in table 2.

Table 2: Data Overview

Data	Description	Source
Wind	Turbine SCADA data from 2001-2004	[49]
Turbine	Bonus B76-2000 Power and Thrust Curves	[49]
Layout	Turbine coordinates for existing layout	[49]
Bathymetry	30'' global bathymetry	[48]
Boundary	Coordinates defining the boundary	[50]
Costs	CAPEX and OPEX cost breakdown	[51, 52]

Figure 4a shows the wind distribution at the site over the four year period and fig. 4b shows the location of the wind farm and the original turbine layout built.

## 4. Results

### 4.1. Verification of Evaluation Function

The existing layout at Middelgrunden Wind Farm is comprised of a single arc running roughly north to south as shown in fig. 4b. The full cost breakdown with a comparison to the published costs is shown in table 3 based on the data provided by Larsen et al. [51] and Middelgrundens Vindmøllelaug

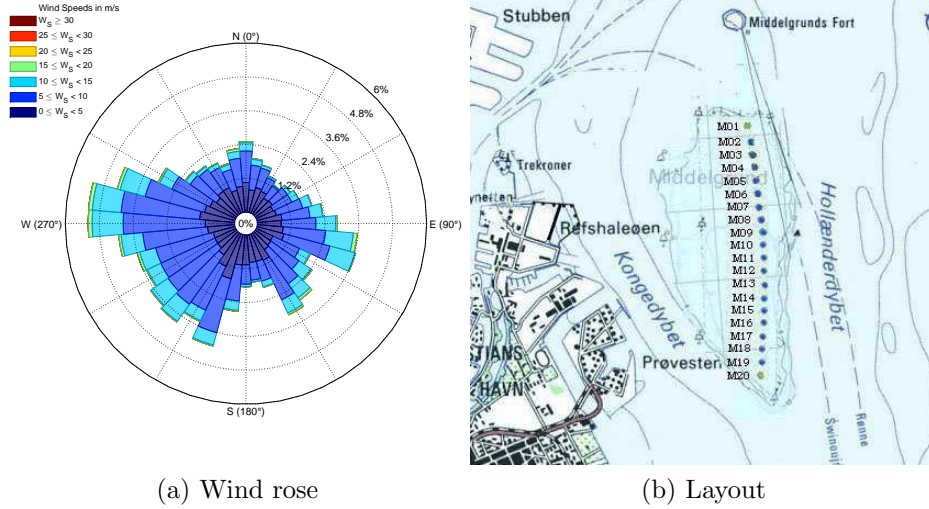


Figure 4: Wind rose for 2001-2004 and existing layout at Middelgrunden Wind Farm.

I/S [52]. The costs provided by Middelgrunden wind farm have been converted to 2011-GBP as this is the currency used in the present model.

From this cost evaluation, the principal areas in which the cost estimate differs from the reported costs are the turbine costs and the O&M costs with the model over-predicting costs compared to the reported results. The reasons for this are discussed further in section 5, however, in this case, these cost differences have a minimal impact on the relative costs of the layouts during the optimization stage as the turbine supply costs are layout independent and the O&M costs only consider the average distance between the turbines and the O&M port.

Using the Larsen wake model as described and the resource data available from 2001-2004, the AEP for this period was computed for the original as-built layout and compared to the reported electricity provided to the grid over this same time period [51]. As the present model does not model or compute the availability of the wind farm, the reported 93% average availability reported over this period was used for the comparison. Table 4 shows the computed and reported AEP (including the wind farm availability) and shows that the AEP estimation for Middelgrunden is accurate with only 0.61% error over the four year period.

Combining these figures, the evaluation of the existing wind farm layout at Middelgrunden wind farm using the developed cost model therefore

Table 3: Middelgrunden - Cost Verification (£k)

	Modeled			Published	Error
	CAPEX	DECEX	OPEX		
Turbine	£35,224			£27,054	30.20%
Turbine Supply	£27,826				
Turbine Installation	£7,398				
Foundation	£13,457			£13,121	2.56%
Foundation Supply	£2,365				
Foundation Installation	£11,092				
Array Cable	£5,319			£4,573	16.30%
Array Cable Supply	£2,188				
Array Cable Installation	£3,131				
Decommissioning		£13,925			
Turbine		£7,218			
Foundation		6,707			
Project Management	£3,949				
Contingency	£9,791				
O&M			£2,424	£798	203.67%

Table 4: Middelgrunden - AEP Verification

	Computed [GWh]	Reported [GWh]	Error
AEP	95.41	96.00	-0.61%

estimates the LCOE of the wind farm to be £92.74/MWh.

#### 4.2. Optimization of Middelgrunden Layout

During the optimization stage, 100% availability is assumed as the present methodology does not consider how the availability of the wind farm is impacted by the layout. As a result, the AEP and LCOE figures reported during the optimization are noticeably higher and lower respectively compared to the verification case considered in section 4.1.

For the given case, both the GA and the PSO were executed three times considering three different sets of constraints defined in section 2 and with the parameters given in tables 5 and 6. In the implemented GA, diversity refers to the proportion of the population that is made up of unique members

508 and elitism to the copying of fittest individuals in the population from one  
509 generation to the next. In the PSO, the velocity must be corrected to ensure  
510 that individuals do not move beyond the search space. This is done using  
511 velocity clamping whereby the velocity is corrected to keep all individuals  
512 within the search space at all times. In the PSO, the continuous velocity must  
513 be converted for the binary implementation of the problem, and therefore a  
514 velocity transfer function is used to convert the velocity to a probability that  
515 a bit is flipped. In the present PSO, no neighborhoods were defined, and  
516 therefore only the global (gBest) neighborhood is used.

517 For all three constraint sets, a minimum separation constraint is applied  
518 to ensure that turbines do not risk colliding and the wind farm boundary  
519 explicitly defines the limits of the wind farm. As the three levels of placement  
520 constraint define the optimization problem differently with different decision  
521 variables and the different representations of the wind farm layout, the design  
522 spaces differ in scope. In general, the continuous mode represents the least  
523 constrained problem with the largest search space. While both the array  
524 and continuous cases make use of real encoded optimization algorithms, the  
525 binary case as it represents a series of binary decisions utilizes binary encoded  
526 optimizers.

Table 5: Genetic Algorithm Parameters

Parameter	Description
Population Size	100
Maximum Generations	1000
Probability of Crossover	Adaptive
Probability of Mutation	Adaptive
Elitism	20%
Stop Criteria	Diversity $\leq 10\%$
	$\frac{\text{Mean Score} - \text{Best Score}}{\text{Best Score}} \leq 0.001$
	Maximum generations reached
	No improvement over 50 generations

527 As no predefined set of allowable turbine positions was used in the devel-  
528 opment of Middelgrunden, a set of allowable turbine positions was defined for  
529 the binary optimizers. To generate this set, a triangulation was performed  
530 on the wind farm area with a target distance between vertices of 100 m. This

Table 6: Particle Swarm Parameters

Parameter	Description
Swarm Size	100
Maximum Generations	1000
Velocity Clamping	Dynamic
Velocity Transfer Function (Binary Encoding)	$T(x) = \left\lfloor \frac{2}{\pi} \times \arctan \left( x \cdot \frac{\pi}{2} \right) \right\rfloor$
Neighborhood Topology	Global (gBest)
Stop Criteria	Diversity $\leq 10\%$ Maximum generations reached No improvement over 50 generations

531 generated 628 allowable turbine positions within the wind farm site as shown  
532 in fig. 5.

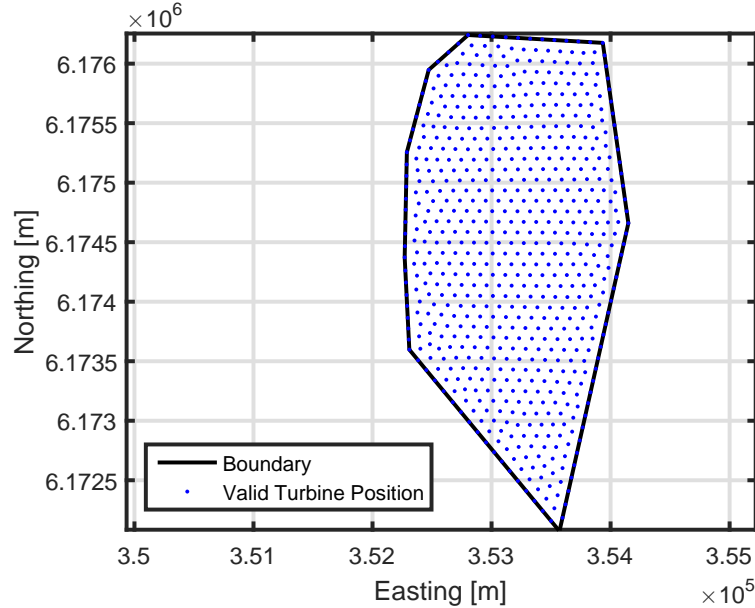


Figure 5: Allowable turbine positions for Middelgrunden Wind Farm when executing the binary decision optimizers.

533 Executing the two optimizers for each of the constraint sets produces the  
534 results shown in table 7 with the produced layouts plotted in fig. 6. Table 7  
535 shows the sum of the discounted cash flow for each layout (i.e. the numerator

536 of eq. (1)), the AEP, the computed LCOE, and the relative improvement  
537 in the LCOE compared to the as built layout evaluated using the present  
538 evaluation function.

Table 7: Layout Optimization of Middelgrunden Wind Farm

Case	Lifetime Cost [£]	AEP [MWh]	LCOE [£/MWh]	Improvement
<i>Existing</i>	$9.15 \times 10^7$	$1.02 \times 10^5$	86.63	-
GA - Array	$9.25 \times 10^7$	$1.07 \times 10^5$	83.69	3.4%
GA - Binary	$9.26 \times 10^7$	$1.05 \times 10^5$	85.40	1.4%
GA - Continuous	$9.23 \times 10^7$	$1.05 \times 10^5$	85.01	1.9%
PSO - Array	$9.22 \times 10^7$	$1.07 \times 10^5$	83.59	3.5%
PSO - Binary	$9.24 \times 10^7$	$1.05 \times 10^5$	85.13	1.7%
PSO - Continuous	$9.24 \times 10^7$	$1.04 \times 10^5$	85.59	1.2%

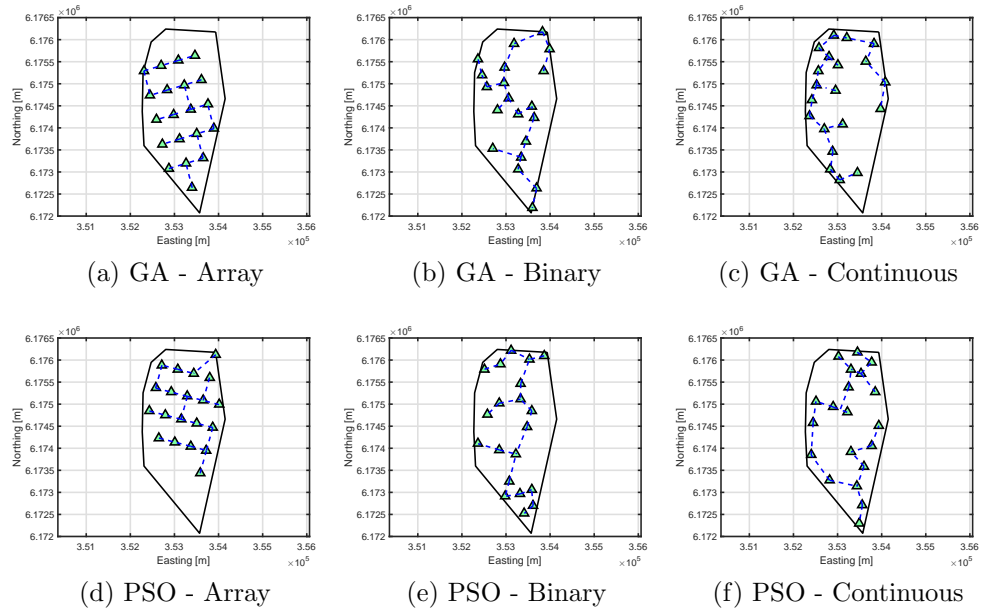


Figure 6: Optimized layouts for Middelgrunden Wind Farm using both optimization algorithms and all three constraint sets.

## 539 5. Discussion

### 540 5.1. Verification of Evaluation Function

541 The verification results presented here showed that the AEP results for  
542 the existing layout match the reported production closely, with less than 1%  
543 error. The costs, however, had very variable error with some elements such  
544 as the foundations having low error on the order of 2.5% while others such as  
545 the turbine costs or O&M costs had over 30% and 200% error respectively.

546 Previous studies of Middelgrunden Wind Farm have also acknowledged  
547 that the turbine costs for this project are much lower than expected even  
548 when compared to projects using similar turbines and constructed during  
549 the same time period [4, 53, 54]. As Middelgrunden is generally thought of  
550 as an outlier when it comes to the incurred turbine costs, it is not unexpected  
551 for the turbine supply costs to carry a relatively high error.

552 In the case of the O&M costs, this difference can be explained by the fact  
553 that the reported figures are based on the O&M spend from two years of  
554 the project while the model estimate is the annual O&M costs anticipated  
555 through the life of the project. The modeled values therefore anticipate that  
556 some major repair works will need to be carried out during the lifetime of  
557 the project. During the two years (2003 and 2004) from which the reported  
558 costs are taken, the wind farm maintained high availability (95.9% and 95.6%  
559 respectively) indicating that no major repair works were carried out. This is  
560 further supported by qualitative reports from the wind farm [51, 52]. These  
561 two years would therefore be expected to have a lower incurred cost than the  
562 modeled values. As the wind farm is now approaching year sixteen of oper-  
563 ation it is likely that costs more representative of the wind farm's lifetime  
564 could be available. Furthermore, the cost relationships used for the opera-  
565 tions and maintenance term are based on reference data for wind farms of  
566 500 MW and 1000 MW and therefore, when extrapolated to a wind farm of  
567 only 40 MW would be expected to have increased error.

568 Though several of the costs for Middelgrunden when estimated using this  
569 tool carry high levels of error, these cost elements are those which do not  
570 include a significant consideration of the layout (i.e. the turbine supply and  
571 O&M costs). These errors therefore will be similar for all layouts evaluated  
572 by the tool, and should not impact the optimization phase of the work.



## 5.2. Optimization Results

From the optimization results, it can be seen that the optimization algorithms regardless of constraint set were able to identify potential improvements with respect to the LCOE when compared to the as-built case. Interestingly, for all the cases executed, the improvement in LCOE comes as a result of an increased AEP and an increase in project cost. This indicates that for Middelgrunden, the improvements in AEP outweigh the increased cost impact and it is important to consider a single metric that is impacted by both the costs and energy production in order to strike a balance between energy production and cost.

From the results of this study, it can be seen that for both optimizers and for all three constraint sets, the LCOE reductions compared to the as-built case are driven by improvements in the AEP. This suggests that for Middelgrunden, a simpler evaluation function focusing on the AEP maximization could still yield strong results, however, without the explicit consideration of the costs, the balance between energy production and project cost could result in unrealistic designs. Comparing across the three constraint sets allows an understanding of how limiting the layout to a regular grid, or a set of predefined allowable turbine positions impacts the quality in layouts. For the present site, these limitations do not significantly restrict the quality of designs that can be produced using the same optimization parameters and therefore indicates to a wind farm developer that these kind of regulatory restrictions would be acceptable. Having said that, there is scope for improving the optimizers through further parameter tuning.

As each of the constraint sets leads to different decision variables and design spaces, it would be expected that different optimization parameters such as the population size would be relevant in order to equally explore the respective search spaces. For the present study, however, the largest population size possible was used for the available computational power. Though the continuous mode was unable to reach the best results it is expected that given sufficient computational power to run the optimizers with larger population/swarm sizes would result in better results. Interestingly, at the end of each optimization run, the LCOE values had converged as would be expected, however, the individual turbine positions were also very similar between the best solutions of each run.

The relative change in discounted cost and AEP combined with information regarding the electricity sale price in each year allows the change in LCOE to be converted to an net present value (NPV). This is desirable as

611 the TOPFARM project, Larsen et al. [55], reported *financial balance* im-  
612 provements for Middelgrunden Wind Farm as a result of optimization of the  
613 wind farm layout. In the TOPFARM project, the financial balance repre-  
614 sents the sum of the NPV improvement and further improvements as a result  
615 of reduced fatigue loading on the wind turbines through improved wake effi-  
616 ciencies. Though the financial balance is not directly the same as the NPV it  
617 does give a grounds for comparing against the TOPFARM results as for all  
618 cases in which the AEP increases, the financial balance improvement would  
619 exceed the NPV improvement. In a report, the TOPFARM project reported  
620 total financial balance improvements on the order of €2.1 million as a result  
621 of improvements to the layout. This would principally be realized due to  
622 reductions in the wake interactions. Using the documented electricity sale  
623 prices in each year of operation [52], the proposed layouts in the present study  
624 correspond to NPV improvements between €1.0 million and €3.5 million if  
625 considering the costs over the lifetime of the project, but revenues from only  
626 the first fifteen years. Projecting the electricity sale price for the remaining  
627 ten years of operation by assuming it remains constant at 2015 values re-  
628 sults in a lifetime NPV improvement between €1.5 million and €4.7 million  
629 depending on which of the six proposed layouts is considered. In the TOP-  
630 FARM project, the project revenues are also projected using an assumed  
631 electricity price based on the subsidy. As the equivalent financial balance  
632 improvements would be expected to be even higher as a result of the reduced  
633 wake loading, it is interesting to highlight the improvements that this work  
634 highlights when compared to TOPFARM.

635 The financial balance term from the TOPFARM project includes these  
636 direct increases in NPV as well as an assessment of the reduced maintenance  
637 costs as a result of reduced fatigue loading on the turbines as a result of the  
638 reduced wake interactions. As the wake efficiency of the layouts proposed by  
639 the present tool is also increased relative to the existing layout (as a result  
640 of the increased AEP) it can be expected that like the TOPFARM results  
641 further value can be assigned to the layouts as a result of the reduced fatigue  
642 loading.

643 Neither TOPFARM nor the present work include the visual impact con-  
644 straints that the real wind farm were forced to deal with and though im-  
645 provements are highlighted, these could still be unacceptable to stakehold-  
646 ers. By comparing the solutions provided by the tool, to the visual impact  
647 restricted layout that was built, it is possible to quantify the impacts of this  
648 constraint allowing the stakeholders to better make decisions. For future

649 projects, quantification of constraints in this way can allow aid in developer  
650 discussions with regulators and stakeholders to ensure that the wind farm  
651 is designed as efficiently as possible given the real constraints faced for that  
652 particular site.

## 653 6. Conclusion

654 This paper has presented a framework for the optimization of offshore  
655 wind farm layouts and the initial result of applying it to Middelgrunden wind  
656 farm. This framework includes a more detailed approach to the estimation  
657 of the LCOE of an offshore wind farm than existing tools and is applicable  
658 to the development of future offshore wind farms. In order to establish the  
659 capabilities of this framework, the existing layout at Middelgrunden wind  
660 farm has been evaluated with less than 1% error in the estimation of the  
661 AEP when compared to published results. On the other hand, for under-  
662 standable reasons, the cost estimation carried higher error, with over 200%  
663 error in OPEX and close to 20% error in the total reported CAPEX ele-  
664 ments. This high error comes in part from the reported OPEX representing  
665 two relatively low cost operational years rather than the average over the  
666 lifetime, and Middelgrunden in general being a wind farm far below average  
667 industry costs. Even though there is relatively high error in some of the cost  
668 components, much of this error is fixed regardless of the layout under con-  
669 sideration and therefore the application of the optimization methodology is  
670 still relevant. Furthermore, the error led to an over-estimation of the project  
671 costs, corresponding to an erroneously high LCOE value of £92.74/MWh.

672 The application of two separate optimization algorithms using three dif-  
673 ferent options for the constraints highlight the capabilities of this framework  
674 and also identifies potential reductions of LCOE in the range of 1-3.5% de-  
675 pending on which optimizer and constraints were used. This reduction in  
676 LCOE can be quite significant for a project developer, equating to an in-  
677 crease of NPV of up to €4.7 million. These results help illustrate the impact  
678 of potential regulatory constraints on wind farm designs. For a site such as  
679 Middelgrunden, the comparison between the layouts designed using this tool  
680 and the original as-built layout illustrate potential improvements in the lay-  
681 out with respect to the LCOE, but also the impact that the social constraints  
682 such as visual impact have on the LCOE.

683 From the results presented, both the GA and PSO produced results of  
684 similar quality indicating that the constraint set deployed has a more signifi-

685 cant impact than which of the two optimizers is deployed. For both optimiz-  
 686 ers and each of the three constraint sets, the final population also had a series  
 687 of layouts that were both similar in LCOE and turbine positions indicating  
 688 that for each of the three constraint sets both optimization algorithms can  
 689 find several layouts which could be of interest to the wind farm developer for  
 690 further investigation.

691 Further development of this framework will explore validation of the eval-  
 692 uation function using additional wind farms, as well as the application of the  
 693 framework to larger wind farms more similar to the next round of develop-  
 694 ment in Europe. Given that the two optimizers never produced the same  
 695 layout, there is an indication that both optimizers for all three constraint  
 696 sets can be further tuned to produce further improvements in LCOE.

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